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Studies on the Fabrication of Surface Composites on Cast Aluminum Alloys using Friction Stir Processing - A Review

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Abstract

Aluminum and its alloys are used extensively in aerospace and automotive industries because of its low density and high strength to weight ratio. Metal matrix composites are a new class of materials that exhibit good wear and erosion resistance properties, higher stiffness and hardness at a lower density as compared to the matrix. However, the presence of the ceramic particles in the metallic matrix makes the matrix brittle Hence, instead of bulk reinforcement, if the ceramic particles would be added to the surface, it could improve the wear and erosion resistance without sacrificing the bulk properties. Dispersion of ceramic particles on metallic substrate surface and the control of its distribution are difficult to achieve by conventional surface treatments. Recently, much attention has been paid to a new surface modification technique named friction stir processing.FSP is a solid state processing technique to obtain a fine-grained microstructure. It is well known that the stirred zone consists of fine and equiaxed grains produced due to dynamic recrystallization. Though FSP has been basically advanced as a grain refinement technique, it is a very attractive process for also fabricating composites. This research aims at fabricating surface composites of SiC/Al2O3 (particulate) on cast aluminum alloys. It will enhance the wear resistance of Al alloy by dispersion of nano-sized particulates on the surface using FSP technique.

Keywords: *Aluminium Alloy; Ceramic; FSP; MMC; Recrystalization; Solid State Processing.*

1. INTRODUCTION

A metal matrix composite (MMC) is normally fabricated using a ductile metal (e.g., Al, Ti or Ni) as the base material, which is reinforced by a ceramic (e.g., alumina, SiC or graphite). Combining the metallic properties such as good ductility and toughness of the matrix with ceramic properties such as high strength, hardness and elastic modulus of the reinforcement, the composites exhibiting high toughness, specific strength and stiffness and good wear resistance can be obtained. MMCs can also have low thermal and electrical conductivity and low sensitivity to temperature variation. Consequently, they have extensitive interest from defense, aerospace and automative industries and have become very promising materials for structural applications as well. The many factors related to the properties of MMCs include the properties of the base material, the type, shape, dimensions, geometric arrangement and volume fraction of the reinforcement and the wettability at the interface of the reinforcement and matrix and the presence/absence of voids (Starke and Staley, 1996).

Particulate reinforced MMCs are promising because of their homogeneous and isotropic material properties, low cost and ability to be formed using conventional metal processing techniques. Among the many ceramic reinforcements SiC has been found to have excellent compability with the Al-matrix. The incorporation of SiC particulates into the aluminium matrix results in increases strength and modulus, thus improving the specific properties of the material. Powder metallurgy and conventional ingot metallurgy, including infiltration techniques are the two commonly employed means by which these composites are fabricated. By powder metallurgy, it is possible to obtain a homogeneous distribution of the reinforcement in the matrix (Corke, 2003).

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1.1.1 Silicon Carbide-Aluminium MMC

One such example of MMC is an aluminium matrix composite reinforced with silicon carbide (Al-SiC). The most important property of aluminium-silicon carbide with reference to the aerospace industry is its strength to weight ratio, which is three times more than mild steel (Carey *et al.* 2009). In addition, composites containing SiC (reinforcing material) and Al (matrix) have high modulus, strength values, wear resistance, high thermal stability, less weight and a more effective load carrying capacity compared to many other materials (Avner, 1997). It is also expected that this composite will exhibit good corrosion/ oxidation properties since silicon carbide forms a protective coating of silicon oxide at 1,200 °C (Lakthin, 1998) and as discussed earlier; aluminium also displays a similar reaction. Therefore, it can be seen that this material offers considerable advantages to the aerospace industry especially in applications that require good thermal and tensile properties.

1.1.2 Factors affecting the properties of AL-SIC

Although the previous section briefly discussed some of the properties of Al-SiC, the composites exact set of properties depend on a number of factors. Apart from the changes in microstructure of matrix and reinforcements that could result from various work hardening or heat treatment processes, this work has identified four factors from the existing that could affect the properties of Al-SiC:

- Reactivity of the matrix and the reinforcing material.
- Type of the reinforcing material.
- Volume fraction of the reinforcing material.
- Distribution of the reinforcing material.

1.1.3 Fabrication of Al-SiC

Chou *et al.* (1985) broadly classify fabrication of MMC's into two categories i.e., Solid Phase and Liquid Phase. Solid Phase methods include Diffusion bonding (such as Cold Isostatic Pressing), Rolling, Extrusion, Hot Isostatic Pressing (HIP) etc., Liquid Phase techniques involve molten metals and examples are Squeeze Casting, Stir Casting, Rheo Casting and various types of infiltration processes. The authors (Chou *et al.* 1985) also advocate the use of multiple methods to fabricate the composite including a combination of certain infiltration techniques, rolling and hot pressing or vacuum infiltration and HIP.

This work recommends the use of Liquid Fabrication techniques for producing Al-SiC, since this melts the aluminium and aids in the formation of an interface layer, which improves certain properties (this discussion will be taken up in more detail later on). Processes such as Stir Casting (Chou *et al.* 1985) and Disintegrated Melt Deposition (DMD) Mahendra Boopathi *et al.* (2013) have been used in fabricating Al-SiC Composites.

1.2 Hot Pressing

Among P/M methods, hot pressing has many advantages. Hot pressing would be substitute for sintering and accordingly, handling and losses due to breakage of the green compacts would be minimized. Closer size control is possible, since volumetric changes, caused by the shrinkage forces or by gas evolution, occur in the hot press die. Thus, subsequent sizing and coining operations become superfluous. Moreover, it can easily yield required heavy weights or high densities without repressing or subsequent working. Physical characteristics obtained are better and comparable in many cases to those of wrought materials Carey *et al.* (2009).

Fully dense metal powder compacts with controlled microstructures can be produced by hot consolidation, in which pressure and heat are applied simultaneously rather than sequentially. Pressure is applied statically or dynamically to the heated powder in one or two opposing directions along a single axis or from all sides. Pressure, while molding the particles into a definite shape, has the important function of making this shape coherent by creating strong particle-contact bonds. Heat, on the other hand, while being allowed to act only in a moderate way to maintain the formed shape, has the equally important function of consolidating and really homogenising the structure by allowing for a sufficient atomic mobility and place interchange to transform the original pattern of agglomerated particles into a recrystallized, uniform grain structure. A controlled atmosphere is required to protect the hot powders or prepressed compacts from oxidation or nitridation by air (Lakthin *et al.* 1998).

If temperature and pressure are sufficiently high and a sufficient period of time is permitted for their action, increased plastic deformation of the powder particles results in completely consolidated compacts whose structures are recrystallized and may be stress-released by a simultaneous or subsequent annealing treatment. The properties of such compacts are dependent upon the amount and rate of diffusion which, in turn, depends on the number and area of the interparticle contacts as well as on the amount of plastic

deformation to which the compact is subjected. Increasing temperature and time at temperature under sustained pressure tend to increase each of the above effects individually, as well as all of them collectively.
If, for example, the structure must be entirely free of voids, this may be achieved by the proper selection of any one of the variables in relation to the other two, such as high pressures at low temperatures for a certain period of time or lower pressures for a shorter time at very high temperatures. The best combination may depend on the plasticity of the metal, on its capacity for alloying with the die material, on the desired grain structure or on the die materials or lubricants available. On the other hand, a controlled porosity may be achieved by the use, at fairly high temperatures, of pressures.

1.3 Aluminium Alloy Properties

Although aircrafts utilise numerous elements in their construction (as discussed in the previous section), perhaps the most important of these is Aluminium. To illustrate, although the Airbus A380 is considered to have the lowest percentage (by weight) of aluminium, it still contains 61 per cent of the element (Carey *et al.* 2009). The main reason for this extensive use is its low weight; density being about one-third of copper or steel alloys (Prabu *et al.* 2006) and its specific gravity being 2.72. According to Prabu *et al.* (2006) aluminium has high strength, ductility, thermal and electrical conductivity. Although the material's electrical conductivity of 34 X 104 ohm^{-1} cm^{-1} may only be around 62 per cent of that of copper's, it is preferred in many industrial situations because of its low weight (Miracle *et al.* 2005). In addition, aluminium also has very good machinability and workability, it can be cast (by any known method), rolled, stamped, spun, drawn, forged, hammered and extruded to almost any shape which makes it easier for manufacturers to produce intricate shapes and patterns required in the aircraft industry. Its ability to resist corrosion through the formation of dense and strong layer of Al_2O_3 (Aluminium oxide) on its surface when exposed to the atmosphere (Mahendra Boopathi *et al.* 2013) is also seen as factor in its extended use. Aluminium's usage is constrained by its limited strength and hardness (hence, being used only in lightly loaded structures) as well as its low melting point- 658 °C (Mahendra Boopathi *et al.* 2013). Additionally, Prabu *et al.* (2006) and also comment about the material's poor stiffness and tribological properties respectively. Thus, the material is combined with various other elements to improve the above-mentioned (and other) properties depending upon its application. An example of such a combination includes a family of materials known as aluminium metal matrix composites.

1.4 Properties extraction of MMC

1.4.1 Reactivity of the matrix and the reinforcing material

The properties at the interface contribute largely to the overall working and behaviour of the composite. It is seen that the load transfer across the interface is responsible for the strength and stiffness; ductility is influenced by relaxation of peak stress near the interface and toughness is dependent on the crack deflection in the interface (Sarkar and Singh, 2012). Therefore, it is essential to study the reactions at the interface whilst considering any MMC. In the case of Al-SiC the primary reaction at the interface is (Iseki *et al.* 1984). According to Tham *et al.* (2001) Al_4C_3 (brittle in nature) is insoluble and therefore forms either as a detached precipitate or a continuous layer around the SiC particles. However, silicon enters the aluminium matrix to form an Al-Si binary alloy.

Table 1. Values of properties with and without the Al_4C_3 layer

Property	without Al_4C_3	without Al_4C_3	Reference
0.2% Yield strength (MPa)	97	103	Tham *et al.* 2001
Ultimate tensile strength (MPa)	113	139	
Work-to-Fracture ($1x10^{-3}$J/mm^2)	17	18	
Work hardening rate	0.0704	0.1122	
Ductility (%)	16	14	

1.4.2 Volume fraction of the reinforcing material

Since the reinforcing material bears a major portion of stress in the MMC (because it's stiffer) Mahendra Boopathi *et al.* (2013), its use in the composite (such as volume fraction, distribution and type) goes a long way in determining the final properties of the material. The study carried out by Mahendra Boopathi *et al.* (2013), considers tensile strength, density, yield strength, elongation and hardness of the MMC with respect to the percentage of the reinforcing material i.e., SiC.

In another study, Neelimadevi *et al.* (2011) also compare the percentage of SiC content with tensile strength and elongation wherein they found that the tensile strength increases with the SiC content up to 15% after which it drops. The percentage of elongation, unlike Chou *et al.* (1985), was proportional to the SiC percentage.

It is believed that the cause of the drop in tensile strength when the SiC content crosses 15% is probably because of the increased (total) area of the interface i.e., number of interfaces which, could result in void nucleation (through interfacial decohesion) and coalescence leading to failure at lower stresses (void nucleation and coalescence are discussed in more detail by Tham *et al.* (2001). With respect to elongation, both the considered studies and show contradicting results. It may be argued that there are some anomalies in the latter study's data since there is always a trade off between strength and ductility and, both cannot rise/fall simultaneously as described in the study (where both tensile strength and elongation percentage are proportional to each other till 15% SiC content).

Table 2. Values of properties with differing SiC content

Property	SiC 5%	SiC 10%	SiC 15%	SiC 20%	Reference
Density (g/cm^2)	2.46	2.31	N/A	N/A	Mahendra Boopathi *et al.* (2013)
Yield Strength (N/mm^2)	236	257	N/A	N/A	
Hardness (BHN)	85.3	87.2	N/A	N/A	
Tensile Strength (N/mm^2)	248	265	N/A	N/A	
Elongation (%)	19.0	18.2	N/A	N/A	
Tensile Strength (N/mm^2)	80.84	88.11	94.21	83.00	Neelima devi *et al.* (2011)
Elongation (%)	5.42	5.92	5.57	6.87	
Hardness (BHN)	40.2	41.1	43.7	44.4	Dave and Kothari, 2013)
Impact strength (N-m)	22	24	N/C	30	

1.4.3 Type of the Reinforcing Material

This work uses the study of Arsenault (1984) in this section and considers two types of SiC reinforcements – fibres and platelets (although the study uses a 6061 alloy, it is argued that these results could be extrapolated to pure aluminium matrix as well since both types of reinforcements in the study have been considered under similar environments).Considering fibre and platelets without any heat treatment from Arsenault's (1984) work, it is seen that even though both the composites demonstrate similar proportional limits (121 MPa), the material with the SiC fibre shows greater yield stress and ultimate tensile strength. However because the fibre's strength was higher, its ductility compared to the platelets were lower. The increase in the properties of the fibre-reinforced composites is a result of the void density percentage, which according to Arsenault [15]is 2% (±1%) for the fibres and 5% (± 2%) for the platelets. Hence, it is seen that the type (shape) of the reinforcement affects the overall properties of the material.

Table 3. Values of properties containing different types of reinforcements

Property	Platelets	Fibres	Reference
Proportional Limit (MPa)	121	121	Arsenault, 1984
Yield Stress (MPa)	162.2	258.8	
Ultimate Tensile Strength (MPa)	249.1	452	
Plastic Strain Elongation (%)	8.1	3.5	

1.4.4 Distribution of the Reinforcement Material

When fabricating MMCs through casting or similar liquid phase techniques, the distribution of the reinforcement material is an important factor to consider as it affects the properties and the quality of the material say that the particle distribution is affected at three stages of the fabrication process i.e., during mixing, after mixing but before solidification (holding) and during solidification. The authors suggest the use of stir casting as it not only helps in the transfer of the particles to the melt but also retains them in a state of suspension. It is also seen that the solidification/cooling rate (of the composite) is important because it influences the distribution of the SiC in the final is got. According to Lloyd *et al.* (1989) when the material is cooled, the SiC particles are rejected at the meniscus and pushed ahead of the solidification front; they are then trapped by converging dendrite arms in the intercellular regions. When the material is cooled rapidly, there is a more homogenous distribution of SiC particles compared to a more slower rate which results in a more clustered distribution (because of more particle pushing) Arsenault *et al.* (1984). According to Dave and Kothari (2013), the distribution of the particles also depends on the wetting (discussed previously). This paper believes that a more homogenous distribution of SiC particles results in less localized damaged (since both the particles and interfaces are more spread out) and also that the clustered particles can result in the formation of

stress concentration regions because the load bearing particles are drawn together.

2. TESTING PROPERTIES

2.1 Ultrasonic Measurements

The speed of wave propagation and energy loss by interactions with material microstructure are key factors in ultrasonic determination of material properties. Relatively small variations of velocity and attenuation can indicate significant property variations. Ultrasonic methods can be used to determine microstructural differences in metals. The testing can be either the measurement of ultrasonic attenuation or the measurement of bulk sound velocity.

Mechanical properties of Al-SiC metal-matrix composites are correlated with metallographic observations. Moreover, the results of mechanical and ultrasonic tests can be associated with metallographic observations. The ultrasonic non-destructive evaluation techniques employed may prove a useful addition for qualifying the homogeneity of SiC distribution.

3. CONCLUSION

It is seen that for any material to be used in aerospace applications, certain criteria must be met. Although the exact set of required properties depend on the specific application, certain properties such as low density, good fatigue performance, and high wear and corrosion resistance are seen as universal requirements for effective functioning in the industry. Therefore, this paper makes a case for Al-SiC MMC and its application in the aerospace industry by exploring its properties. One of the main reasons for its consideration was the material's low density and its good wear (and corrosion) resistance.

From the literature, it is seen that these materials can be manufactured by either solid phase or liquid phase methods. This work, however, recommends the latter as they seem to show better results while being tested (if certain issues such as wettability are overcome). But for the most effective results, factors such as interface reactions, volume fraction of SiC, type (shape) of the reinforcing material and its distribution in the matrix must be taken into consideration during design, material selection and fabrication processes because when these factors are considered and the right selections made, it is genuinely believed that Al-SiC has tremendous potential for application (such as the fuselage skin) in the aerospace industry.

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